CSC-3132

The Clear Flow Matrix: An Effective Production Control Technique Using Crew Level Planning

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Abstract

Cost overruns and schedule delays are commonplace in the building construction industry and often result from poor production management and control in the field. Production management and control systems in construction should provide a framework which is intuitive and visually evident for all levels of management and trade supervisors. This paper presents the clear flow matrix (CFMx), a novel production management and control technique for building construction. The CFMx consists of a matrix integration of the trade activities and locations wherein time and workflow rhythm are represented through the progress of a unique balanced workfront, which balances client completion demand and trade contractor operations efficiency as trade work progresses through the building areas. Work sampling analysis (WSA) conducted on three CFMx building projects including a hospital, a school and a multi-family development, confirmed the effectiveness achieved by the CFMx through direct work ratios exceeding reported industry averages. Questionnaire/interviews of trade supervisors and managers from these projects verified that the matrix-based tool is visually evident, intuitive and easily implemented in the field without the need for extensive knowledge of scheduling concepts or training.

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Introduction

In building construction, the process of planning, scheduling and controlling is complicated and ever-changing, especially for interior finishes, which require careful management attention, so that the various trades can perform the work safely and with quality in the appropriate order necessary to complete the project. That is, trade workers from the several different subcontractors must pass through each room of the building and complete the work in the proper sequence at the proper time. Therefore, a good construction plan with its embedded production plan is fundamental to the successful execution of construction projects.

Since 1950, construction planning has been a topic for research resulting in new methodologies and techniques useful in planning, scheduling, production control of the work activities as well as overall management of construction projects. Among them, the critical path method (CPM) has been adopted by the construction industry as a standard model for the scheduling calculations required to determine project completion dates under a set of project and management circumstances. However, CPM scheduling software programs commonly available and applied to building construction projects present certain limitations for managing construction projects. One of the first authors to mention these limitations was George Birrell (Birrell, 1980) who described these issues as follows: CPM fails to handle resource allocation; ignores the workflow management of the project, making this technique incapable of maintaining crew work continuity. Birrell also stated that CPM focuses on the duration of activities and disregards the cost of the project. Furthermore, current CPM applications often use a Gantt chart output format to display and track activities and completion status. This format is sometimes difficult to understand, especially when projects have many activities producing many pages of schedule output. As construction projects are dynamic and often include uncertain processes, the schedule and production of the work should be reviewed and updated on a regular basis. Thus, updating of CPM schedules to reflect actual and forecast production progress is often considered to be a cumbersome process requiring a significant amount of effort to re-plan.

The selected production management and control program employed to implement the master project schedule should be intuitive, easily managed and capable of effectively communicating project status to all parties including managers, trade supervisors and trade workers. More specifically, it should depict the flow of trades through available work locations of the project focusing attention on production flow. The several trade steps at the many locations in a large building may produce a large number of schedule data points of trade/location/work activities for monitoring during construction. The production management and control system should effectively deal with this dimensionality problem and be readily available for review and use at the work face, with or without digital technology.

Having encountered production control issues common in building construction, construction managers recognized this need and a new production management and control system has been created, called the *clear flow matrix*. The CFMx integrates work locations and trade activities in a production management and control matrix incorporating useful manufacturing concepts of throughput, production flow, buffers and control-time planning. The matrix design of CFMx is an effective and deployable format which communicates schedule and production status of all flow units of production according to the control-time period suitable for the size of the project.

The purpose of this paper is to present the CFMx and assess its performance in application to building construction projects and review the relevant theories of production systems used in developing the CFMx. This research conducted by the University of Texas at Austin used two methods of data collection to assess the effectiveness of the CFMx. First, interviews and questionnaires obtained from foremen and project managers of trade contractors who have worked on projects utilizing the CFMx are used to assess industry-user effectiveness opinions. Second, work sampling analysis observations of construction worker behavior are collected from CFMx projects and categorized according to: direct work, idle, transport, personal, travel and instruction. The WSA results from CFMx projects are then compared to similar WSA research conducted by Gong, et al., (2010), which provides data of WSA outcomes of Texas building construction projects sampled from 1972 to 2008.

Literature Review

Flow in Construction

The term *flow* has been more recently used by construction managers. However, the understanding of workflow in construction is not so straightforward as it is in manufacturing. In factories, products usually follow a production line, moving from workstation to workstation where workers or machines transform the raw materials into final products; in construction projects, however, products are fixed to the ground, making workers, instead of products, move through different locations (Kaalsas & Bolviken, 2010).

Researchers have also defined *flow* in differing but correlated ways in their descriptions of production systems. Firstly, Shingo (1989) from the automotive manufacturing industry, defines production systems as a chain of events that combines two types of flow: the process flow and the operations flow. He clarifies the difference between them through a two-dimensional chart where the vertical axis represents process flow, and the horizontal axis is operations flow (Figure 1 below). Despite the discrepancies between the automotive manufacturing and the construction industries, the two types of flow defined by Shingo—process, and operations—are also seen in construction projects. Process flow in manufacturing is the transformation of raw materials into manufactured products; operations flow in manufacturing is the work of a succession of workers on the incomplete products. The progress of work at a construction project is achieved as identified areas of the job site are converted into the final product for the owner and correlates to the process flow of Shingo. On the other hand, operations flow of Shingo correlates to the work of each trade on the identified work areas of the construction project.

In 2000, Koskela described the TFV theory (transformation, flow, and value generation) in regard to construction management. Although the flow concept had been used before by lean philosophy, the TFV theory states that these three elements must be considered together and balanced (Bertelsen & Koskela, 2002). Koskela defines that *flow* can be considered any movement in the production system, which is composed of four elements: waiting, inspection, movement, and process. This means that products will spend available production time in one of these four production states, in which only processing is not considered waste. The chart below depicts an example of a health care project with the two types of flow from Shingo (operations and process) and the four steps of production defined by Koskela as trade crews move sequentially through locations as time progresses.

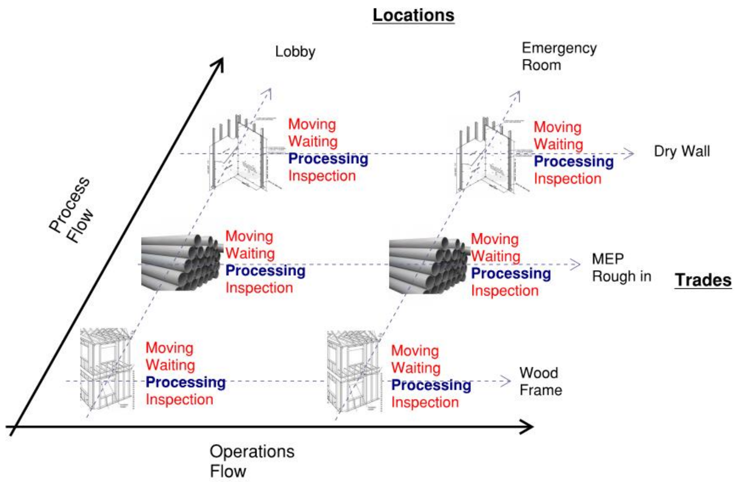


Figure 1 – Shingo's production system adapted to the construction industry (adapted from Shingo, 1989)

In 2016, Modig & Åhlström (2016) presented a new perspective of production systems showing the interplay of the tension between resource efficiency and flow efficiency. They describe resource efficiency as resource use during a time period. Efficient use of resources is synonymous with production efficiency, or operations flow efficiency described by Shingo. Conversely, their flow efficiency focuses on the amount of time flow units are processed in a production system. Timely and productive flow of the several trade work crews through a location increases throughput and improves flow efficiency and is equivalent to process flow efficiency of Shingo.

Taking into consideration some particular differences between construction and manufacturing, Sacks (2016) amended Shingo´s concepts, creating the PPO model (portfolio, process, and operations). The PPO model considers a three-dimensional model of the process and operations chart from Shingo where the added third axis of portfolio work represents the flow of works in various locations through all available work contracts of project participants. The PPO model can be applied not only for shifting trade workers through available portfolio contracts but also for relocating any type of resources across available projects. Figure 2 below depicts the three-dimensional PPO model, in which the vertical axis represents the portfolio of projects.

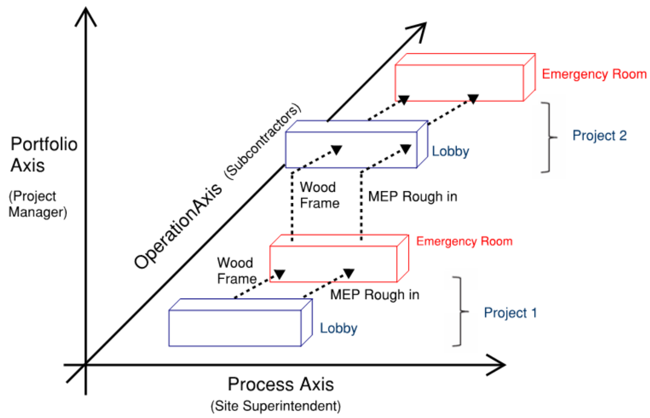


Figure 2: Scheme of flows in construction projects (adapted from Sacks, 2016)

Sacks (2016) correlates these three axes of the PPO model with the primary management functions required on construction job sites. First, CM/GC project managers focus on the portfolio axis, where they conduct simultaneously their various contracts with their clients through the work of suppliers and subcontractors. However, they also seek to efficiently deliver a completed project for each individual client as represented on the process flow axis. The CM/GC site superintendents centralize their work efforts on the process axis of their individual projects by completing work areas to advance individual project completion. The subcontractor trade managers focus not only on high productivity on each particular project (operations axis), but also on utilizing all of their available resources efficiently across all of their projects within their portfolio axis.

Work Sampling Analysis

In 2018, a research project was conducted by the University of Texas at Austin to investigate the effectiveness of the clear flow matrix as applied to building construction projects. According to Parker & Oglesby (1972), a direct way to assess the effectiveness of management techniques on construction projects is to measure utilization of project resources including equipment, labor, time and materials. Construction managers may not be able to manage each of these resources during field production; for example, materials may be purchased by off-site administrative staffs; project design plans and specifications controlled by the design team determine material quantities and qualities; and construction equipment utilization is part of field supervision to manage. Thus, labor along with time are the principal field production system elements that construction managers may effectively manage on job sites through production management and control in order to best deliver the completed works in compliance with the master project schedule. Therefore, analyzing the efficiency of labor utilization on job sites is one way to investigate the management effectiveness of construction management systems on projects. Accordingly, this research reports on a study that uses labor utilization as a direct measurement of the effectiveness of the CFMx as a production management and control technique.

Work sampling analysis is a labor-effectiveness review technique that measures the efficiency of time utilization of craftsmen on job sites (Gong et al.,2011) by observing and recording how the construction workers are spending their time on the projects. The procedure for collecting WSA data involves performing many random (time, location, trade) snapshot observations of worker activities on the job site. Categorization of these observations may be done in several ways; this research classifies the WSA data into three principal categories: productive work, supportive work and personal/idle time. The supportive category is further subdivided into travel, transport, and instruction. The descriptions of categories and subcategories are shown in Table 1 below:

Category	Subcategory	General Description
Productive	Direct work	Workers doing physical effort directed towards an activity or physically assisting in these activities.
Supportive	Transport	Transporting of tools, equipment or material from one part to another.
	Travel	Walking with empty handed without tools, materials or technical information.
	Instruction	Receiving assignments and determining requirements prior to perform tasks.
Idle	Personal	Personal time taken or idleness taken during normal work hours and normally not attentive to work.
	Idle	Periods of waiting or idleness.

Table 1: Categories of work sampling used in this research

WSA data indicate the percentage of useful time that workers are spending on work activities of the project. Since time is the natural unit of flow in construction (Koskela, 2000), WSA also provides an effective method of measuring efficiency of management and production systems on construction projects as shown in the chart below (Figure 3).

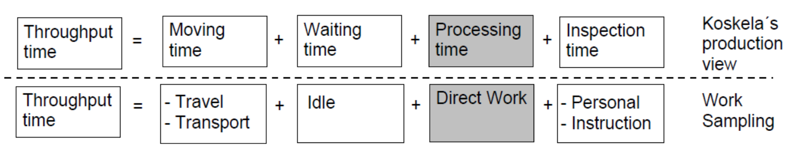


Figure 3: Harmony between Koskela's production view and work sampling analysis

Figure 3 above shows that processing time is the only value producing use of worker time on construction projects and is represented by the direct work measurements in WSA. Furthermore, Modig & Åhlström (2016) suggest that flow efficiency is the capacity of a production system to generate value producing time during system throughput time; and Wernick and Lidelöw (2016) represent flow efficiency as the ratio of value producing time to total throughput time. Thus, if the value producing time is measured by direct work and throughput time is the total time in the process, then work sampling outcomes can be a measurement of flow efficiency, as shown in the relationship of Figure 4 below.

Wernicke and Lidelow (2016) ↓ Work Sampling Analysis ↓

$$Flow\ Efficiency = \frac{\sum Value\ added\ times}{Throughput\ time} = \frac{Direct\ Work}{D.Work + Travel + Trans + Instr. + Pers. + Idle}$$

Figure 4: Flow efficiency and work sampling analysis relationship

The work of Parker & Oglesby, 1972, suggests that the best measure of construction project management system effectiveness is resource utilization on the project. Further, it is suggested that WSA data may be used to measure construction project management system effectiveness in the use of resources. Higher or improved direct work ratios of construction personnel indicate that the embedded production management and control system used on the project provides a construction culture and a supporting technical framework which empowers trade personnel to spend more of their time on productive work. As shown above in Figure 4, trade workers working productively improves flow efficiency by reducing wasteful uses of time. These same reductions in wasted time also provide opportunities for trade resource efficiency improvement. Therefore, higher direct work ratios from WSA may indicate a production plan that better balances flow efficiency (process flow) and resource efficiency (operations flow) than production plans on other building construction projects with lower direct work ratios. Of course, effective control of productivity remains with trade supervisors; that is, WSA direct work snapshot observations of trade workers actively working on items of production does not mean the workers are producing completed work in alignment with standard, or expected, or estimated production rates.

The Clear Flow Matrix

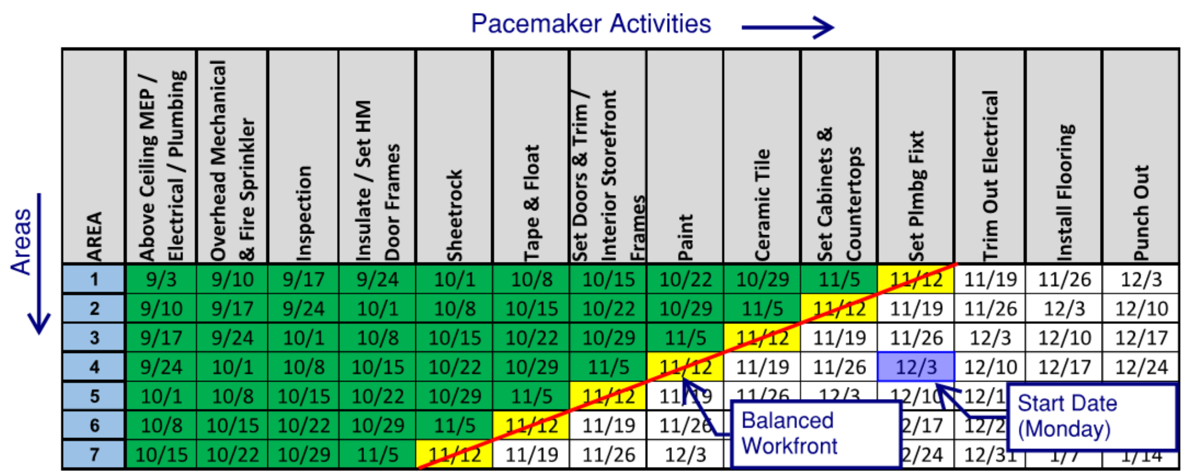
Introduction

In the construction industry, home office construction managers commonly face difficulties with managing production control and schedule because projects are often located some distance from home office. To ensure that production control and schedule techniques are properly executed in the construction process, they must be easily managed and intuitive. More specifically, it should be legible for trade supervisors. Straightforward and visual tools for depicting the project schedule and production management supporting the project delivery were needed for use by the site supervisors. Thus, the clear flow matrix production management and control system was developed for this purpose.

How the Clear Flow Matrix Works

The clear flow matrix production control method provides a clear visual and intuitive mechanism for managing and controlling the production of building works. This mechanism uses a simple two-dimensional matrix of work locations and trade work items with an embedded third dimension of time represented by the start date for each trade/location-area item. The first step in composing the CFMx is the identification of appropriate finish location-areas by carefully segmenting the entire project into smaller areas. These location-areas are listed in the first column of the CFMx as identifiers. The work items to be performed are identified in the first-row labels and are referred to as *pacemaker activities*, and are naming conveniences, each of which represents a description of the major work to be performed in the pacemaker activity, but other trade work may also be included in the indicated pacemaker activity. For example, in steel-framed construction work, the "MEP rough-in" pacemaker activity could include work from multiple trades including: mechanical, electrical, D/W/V piping and potable water plumbing, data, telecommunication, fire sprinkler, medical gas, owner equipment rough-in and other such trade work. Thus, the entire pacemaker activity sequence of works represents all of the trade-work required for completing the project. The order of the pacemaker activities as placed in the matrix from left-to-right corresponds with the correct logical sequence of activities necessary to build the segmented location-areas. Thus, all work within each building area segment will follow the same sequence of work typically encountered in the installation of building finishes. The physical sequence or flow of location-areas is determined by the construction manager in consultation with trade managers and in compliance with the master project schedule.

The functional cells in the CFMx are labeled with the scheduled start date of each of the indicated pacemaker activities for the area location segment and therefore durations and completion dates of the location-area work segments may also be determined from the matrix. The duration selected for each cell of the matrix should be set by the construction manager according to the size of the project and the frequency of management review required for the work. In most applications, the work of each trade involved in the indicated pacemaker activity within the each of the location-areas is to be completed in a period of one week. This control period frequency corresponds with weekly project meetings typically encountered on most building construction projects. The diagonal line formed by connecting cells with the same Monday date indicates a date line that represents planned work for the indicated week. Figure 5 below represents CFMx schedule and its nomenclature.



AREA	Above Ceiling MEP / Electrical / Plumbing	Overhead Mechanical & Fire Sprinkler	Inspection	Insulate / Set HM Door Frames	Sheetrock	Tape & Float	Set Doors & Trim / Interior Storefront Frames	Paint	Ceramic Tile	Set Cabinets & Countertops	Set Plmbg Fixt	Trim Out Electrical	Install Flooring	Punch Out
1	9/3	9/10	9/17	9/24	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3
2	9/10	9/17	9/24	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10
3	9/17	9/24	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17
4	9/24	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24
5	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/1[illegible]	[illegible]	[illegible]
6	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	[illegible]	[illegible]	[illegible]2/17	12/2[illegible]	[illegible]	[illegible]
7	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	[illegible]	[illegible]	[illegible]2/24	12/31	1/7	1/14

Figure 5: Representation of the clear flow matrix schedule

During the construction progress of the project, this date line is referred to as the *balanced workfront* and it depicts the scheduled work status at the indicated date for the various area locations. As time and the project work advance, the balanced workfront moves forward with time and represents the work planned/completed for the status date in each CFMx cell. Any scheduled work that is incomplete and is behind the balanced workfront status date is considered to be late. All work activities that are underway but incomplete during the indicated week are marked with yellow and the activities already finished are marked in green. Late activities behind the balanced workfront are marked in red. In this way, clear and simple identification of late (behind schedule) work activities by location-area and the number of weeks that such activities are behind schedule are evident by visual review of the CFMx and the balanced workfront. Thus, the schedule update and progress review for each scheduled pacemaker work activity is binary; that is, scheduled work in the indicated location-area for the week is either complete or incomplete and therefore on schedule or late.

Updating the status of the matrix is accomplished by marking each cell of the matrix with colors according to the scheduled status of the cell in relation to the status date and the balanced workfront. Figures 6 and 7 below show this schedule status and update dynamic of the matrix for the first two weeks of an example project in which the project started on Monday, September 3rd. In the example, the first activity to be started on the project start date is “Above Ceiling MEP/Electrical and Plumbing.” Therefore, only the first cell must be marked with yellow indicating current progress has commenced. For the next week, Monday, September 10th, the work represented by the first activity moves to the next area in the scheduled location-area sequence, and the next pacemaker activity, which is “Overhead Mechanical/Fire Sprinkler,” is initiated in the first location-area just completed by the first trade. The finished area from the previous week must be colored with green. In the third week of the project, the third pacemaker activity, “Inspection,” is started on the project and the precedent activities move forward to the next areas. This flow of pacemaker activities through the location-areas continues until the completion date of the project.

1st Week

Pacemaker Activities →

Segmented Areas

AREA	Above Ceiling MEP / Electrical / Plumbing	Overhead Mechanical & Fire Sprinkler	Inspection	Insulate / Set HM Door Frames	Sheetrock	Tape & Float	Set Doors & Trim / Interior Storefront Frames	Paint	Ceramic Tile	Set Cabinets & Countertops	Set Plmbg Fixt	Trim Out Electrical	Install Flooring	Punch Out
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3	9/17	9/24	[illegible]	[illegible]	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17
4	9/24	10/1	[illegible]	[illegible]	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24
5	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24	12/31
6	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24	12/31	1/7
7	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24	12/31	1/7	1/14

Monday

Figure 6: Representation of the clear flow matrix in the first week of the project

1st Week | 2nd Week | Pacemaker Activities →

Segmented Areas

AREA	Above Ceiling MEP / Electrical / Plumbing	Overhead Mechanical & Fire Sprinkler	Inspection	Insulate / Set HM Door Frames	Sheetrock	Tape & Float	Set Doors & Trim / Interior Storefront Frames	Paint	Ceramic Tile	Set Cabinets & Countertops	Set Plmbg Fixt	Trim Out Electrical	Install Flooring	Punch Out
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3	9/17	9/24	10/1	10/8	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17
4	9/24	10/1	[illegible]	[illegible]	[illegible]	[illegible]	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24
5	10/1	10/8	[illegible]	[illegible]	[illegible]	[illegible]	11/12	11/19	11/26	12/3	12/10	12/17	12/24	12/31
6	10/8	10/15	[illegible]	[illegible]	[illegible]	[illegible]	11/19	11/26	12/3	12/10	12/17	12/24	12/31	1/7
7	10/15	10/22	10/29	11/5	11/12	11/19	11/26	12/3	12/10	12/17	12/24	12/31	1/7	1/14

Balanced WorkFront (Mondays)

Figure 7: Representation of the clear flow matrix in the second week of the project

Figures 8 and 9 below present the application of the clear flow matrix to a healthcare project, which was in 2018. Figure 8 shows the segmentation of the entire floor plan of the project into distinct location-areas of work for utilization in scheduling and production control using the CFMx. These location-areas and appropriate pacemaker finish activities were then used to develop the CFMx for the project indicated in Figure 9. This example represents the status of a healthcare project as of October 29, 2018 (Monday). Thus, the status review of construction progress is straightforward and is determined by examining the amount of work that is complete, incomplete or late by comparing completion status with the balanced workfront. Bottlenecks and anticipated delay information may be obtained by counting cells of incomplete and late work that lag behind the scheduled balanced workfront. For instance, assuming the project presented in Figures 8 and 9, the activity “Sheetrock” is two weeks behind schedule, and the area 1 is three weeks delayed. In a similar fashion, is also possible to recognize activity acceleration, or work that is being performed ahead of schedule. In the same project example, the activity “Insulate/Set HM door frame” is one week ahead of the balanced workfront. As mentioned previously, the visual representation of production using a CPM schedule usually requires the use of a large number of documents, culminating in the eventual confusion with regards to the understanding of the schedule of the project as a whole and how the project schedule relates to actual realized field production. On the other hand, through the use of the CFMx, the overall production plan that complements the project CPM schedule can be precisely represented in just a single page.

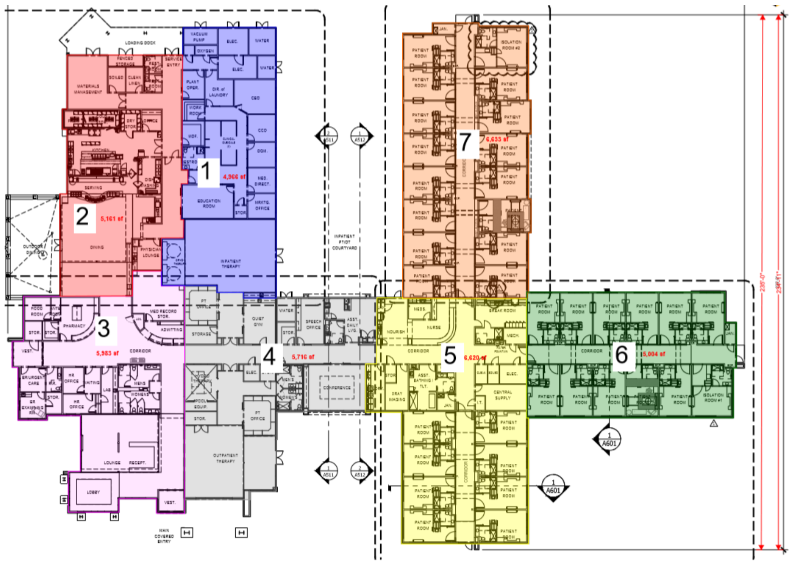

Figure 8: Segmented areas for the CFMx of a healthcare project

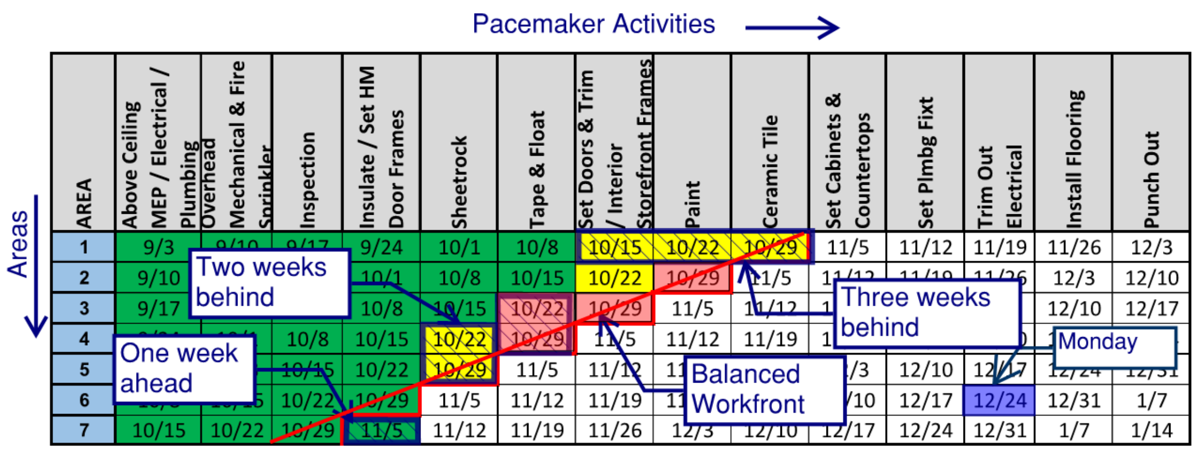

Figure 9: CFMx of a health care project

In construction projects, process flow is associated with the efficiency of the handoff of production in one location-area to the next trade while operations flow is related to the operational efficiency of each trade as any single trade moves through the sequence of location-areas. The balance between these two types of flow is required for efficient production of the completed project. This balance can be achieved through application of the balanced workfront.

The example clear flow matrix shown below as (Figure 10) presents the tension between the priorities of the owner for completion of project segments and the trade contractors desire for operations efficiency. The owner's desire to have a completed project is best served by assuring high process efficiency with a focus on completing building areas to decrease throughput time thereby assuring a faster completion date of the project. Conversely, trade contractors focus on high operations efficiency in order to finish their work rapidly to reduce their labor cost and to move available crews to other portfolio contracts. With the reference of the CFMx presented below, a production plan which focuses only on process flow efficiency or operations flow efficiency will not effectively produce the completed product for the client. Producing completed areas in the building (units or location-areas) without completion of other location-areas wastes time, just as completing the entire work of each trade in turn also wastes time. Indeed, it is not possible to complete building finishes unless the trade sequence required for the work is respected. The client cannot accept the building until the entire building is completed. The objective is then to develop and follow a production plan framework that balances the two types of flow so that the client and construction team members are served in a balanced way.

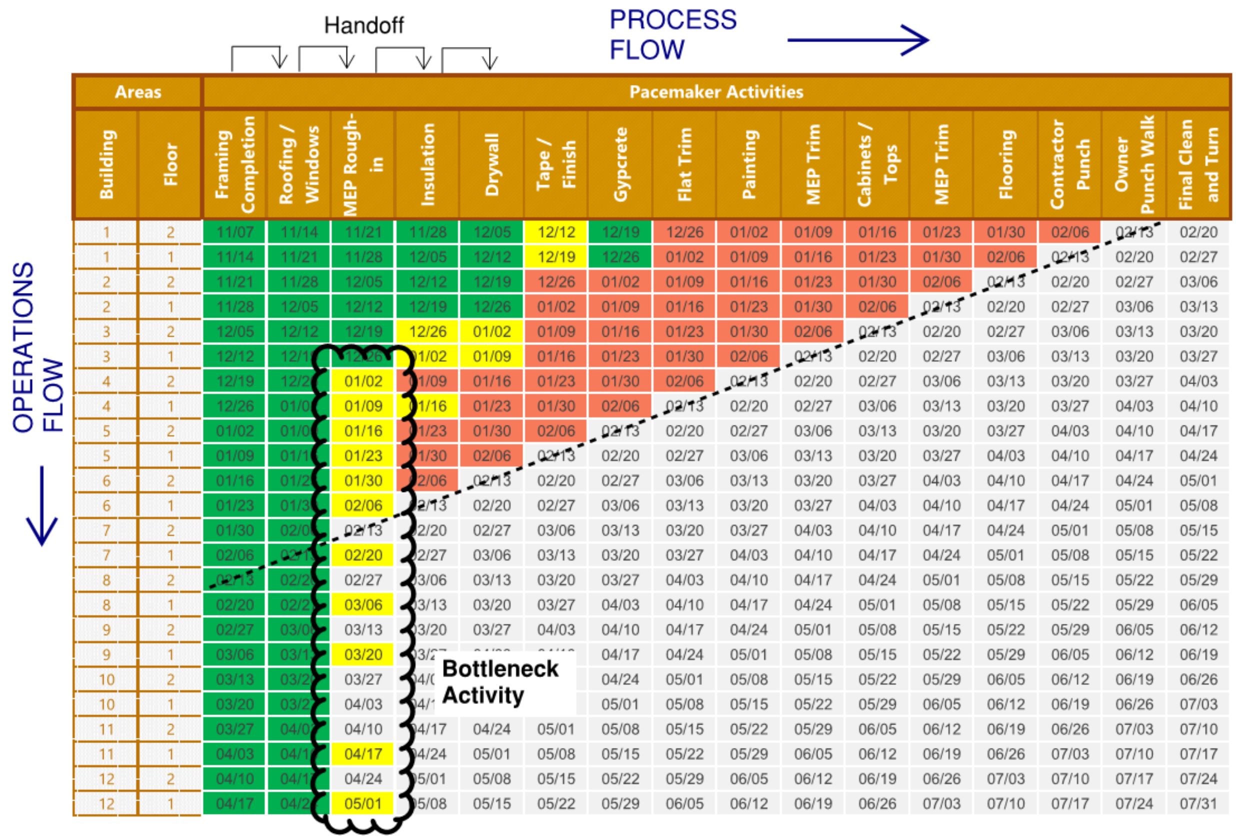

Figure 10: Clear flow matrix of a 12 building multifamily residential project

In the earlier stages of the project, the same crews begin to move from area to area with little disruption as shown vertically on the matrix in Figure 10 and highlighted as "Operations Flow" since the earliest trades are not dependent on the completion of work of other trades in order to start their work in each location-area. As the initial crews complete a location-area (location or unit) and move to the next unit of work, they prepare to hand off the area/unit to the next crews. This interaction between trades along the balanced workfront represents management efforts to *balance* the tension between process flow and operations flow as discussed herein, so that completed location-areas are turned over to the client according to the master project schedule. The handoff must be managed correctly for the process flow of each of the completing location-area unit (shown horizontally) to progress at the same efficiency as in the earlier stages of trade work and completing location-area work.

The CFMx shown above reflects the status of a project comprised of 12 wood-framed 2-story apartment buildings on the date 02/13. This project was several months behind schedule, and the progress on the project was not sufficient to regain the original schedule completion date; thus, the project was effectively out of control. For this reason, the owner of the project engaged a consulting construction manager to analyze the project progress and schedule completion status. The original technique used for scheduling and production control on the project was a CPM network-based Gantt bar-chart depicting detailed schedule activities for each of the buildings. The resulting schedule was presented in some 38 letter-sized pages of Gantt chart schedule information.

The consulting construction manager reviewed in the field the current completion status of each building of the project and input this data into a CFMx production control plan to establish a projected date for the completion of the project. This effort generated only one page of information that represents the completion schedule for interior finishes for the entire project beginning with framing completion. This example use of the CFMx production plan highlights the ease with which managers may employ the CFMx to identify not only the delays, bottlenecks and the trades responsible for delays, but also the appropriate trades and location-areas required for steady acceleration needed to complete the project as delaying bottlenecks are alleviated. The status of work completed on the project indicates clearly the poor results that may result in projects which do not focus attention on both axes of project flow, process flow and operations flow, on a frequent production control period, perhaps weekly, basis.

At this multifamily residential project, the first two trades of the project accelerated their work and partially completed their location-area activities ahead of schedule and then effectively left the project. However, even with the supposed high operations efficiency of these two trades, the project was still delayed because of bottlenecks that developed later and for re-entrant work required to complete instances of incomplete work of the supposed operations efficient trades now departed from the project. This situation highlights the need for having a balance between trades operation (operations flow) and handoff process (process flow). The CFMx prepared for this project was employed by the consulting construction manager and the client to eliminate the bottlenecks and then to smoothly accelerate completion of the project.

Balanced Workfront

As the project progresses to completion, new trades start to work on the project while the initial trades move into subsequent areas as handoffs are completed. As more areas of the project become engaged in the finish work, successfully completed handoffs and make-ready are critical to prevent trade contractor issues such as: out of sequence work; trade stacking; abandonment of the project for other portfolio work; working ahead in inactive areas due to instances of incomplete handoff or make-ready; or re-entrant work due to incomplete or incorrect work. The construction industry needs a good production management system to avoid these unwelcome situations. Ideally, trade work crews should be sized to perform their work in the specified time available for their work in the project master schedule, and as their work production is further refined in the production management plan by location. This crew-levelled resource loading approach balances the construction manager and owner need for project completion with the trade contractor goal of reasonably effective use of their labor resource and management time. The balanced workfront reveals the tension between operations flow and process flow at any selected time as the progress of the project unfolds according to the master project schedule.

Furthermore, the balanced workfront can depict the work loading, or work in process (WIP), throughout the course of the project. At the beginning of the project, only a single location-pacemaker activity is under construction. Each week, another location-area of construction is added to the construction effort until all areas are under construction and then total work load diminishes as areas are completed sequentially. This status is indicated along the balanced workfront or diagonal dateline that advances with time from the first pacemaker activity and first location-area through the last pacemaker activity and last area. The starting date of each location-pacemaker activity is indicated by the date in the cell along this diagonal dateline which again represents the balanced workfront for the indicated date. The work undertaken along the balanced workfront is the amount of WIP that just delivers the completed project in accordance with the master project schedule, and therefore represents the critical WIP expressed as a function of schedule date. As time and completed work of the project advance, the number of current work locations (yellow cells) increases from a single location of work at the beginning of the project until work is underway in all location-areas. The actual peaking of WIP, stabilization of WIP and the decline in WIP depends upon the number of location-areas and pacemaker activities. The balanced workfront identifies the variation of workload through the duration of the project. Figure 11 below illustrates three different situations.

Areas	Above Ceiling Electrical & Plumbing	Fire Sprinkler	Overhead Mechanical / Door Frame Install	Inspection	Insulate	Sheetrock / Ceramic Tile	Tape & Float	Paint	Interior Storefront Frames / Cabinets & Countertops	Set Plumbing Fixtures / MEP Trim Out	Install Flooring / Interior Doors
1	09/03	09/10	09/17	09/24	10/01	10/08	10/15	10/22	10/29	11/05	11/12
2	09/10	09/17	09/24	10/01	10/08	10/15	10/22	10/29	11/05	11/12	11/19
3	09/17	09/24	10/01	10/08	10/15	10/22	10/29	11/05	11/12	11/19	11/26
4	09/24	10/01	10/08	10/15	10/22	10/29	11/05	11/12	11/19	11/26	12/03
5	10/01	[illegible]	10/15	10/22	10/29	[illegible]	[illegible]	11/19	11/26	12/03	12/10
6	10/08	[illegible]	10/22	10/29	11/05	[illegible]	[illegible]	11/26	12/03	12/10	12/17
7	10/15	10/22	10/29	11/05	11/12	[illegible]	[illegible]	12/03	12/10	12/17	12/24

Increase of work areas

Work areas remain the same

Decrease of work areas

Figure 11: Representation of the workload of the project by the balanced workfront

The CFMx and its embedded tool, the balanced workfront, can be used to generate a manpower histogram for the project. Assuming the same matrix schedule, but with no dates presented, project managers from trade contractors can fill up the blank cells with information regarding manpower for each segmented location-area. For those pacemaker activities that have more than one trade working, it is necessary to sum up manpower information from the various trades. For instance, the first activity in the example below (Figure 12) contains the electrical and plumbing trades and the number of workers for that column has to be the sum of the workers from each of the trades. It can also be noted that manpower matrix is related to the CFMx schedule and project managers may access manpower information for any week of the project. As demonstrated earlier, the BWF is a diagonal line of cells with the same date in the matrix. Using this same concept, the manpower of each week is the sum of the diagonal cells on the BWF or dateline for the indicated date. Figure 12 shows two examples of how the manpower spreadsheet interacts with the CFMx schedule. In this example, the green line represents the balanced workfront for the week of 10/08 and indicates that 18 trade workers are involved during that week. Another example is shown by the orange line, which represents the week of 11/12. Once the spreadsheet is completed with manpower information, the manpower histogram can be generated for the entire project.

Manpower input

BWF Line

BWF Line

Manpower	Week	Areas	Above Ceiling Electrical & Plumbing	Fire Sprinkler	Overhead Mechanical / Door Frame Install	Inspection	Insulate	Sheetrock / Ceramic Tile	Tape & Float	Paint	Interior Storefront Frames / Cabinets & Countertops	Set Plumbing Fixtures / MEP Trim Out	Install Flooring / Interior Doors
5	09/03	1	5	2	4	1	2	4	2	2	3	4	3
7	09/10	2	5	2	4	1	2	4	2	2	3	4	3
11	09/17	3	5	2	4	1	2	4	2	2	3	4	3
12	09/24	4	5	2	4	1	2	4	2	2	3	4	3
14	10/01	5	5	2	4	1	2	4	2	2	3	4	3
18	10/08	6	5	2	4	1	2	4	2	2	3	4	3
20	10/15	7	5	2	4	1	2	4	2	2	3	4	3
		Week	10/15	10/22	10/29	11/05	11/12	11/19	11/26	12/03	12/10	12/17	12/24
		Manpower	20	17	18	18	20	18	14	12	10	7	3

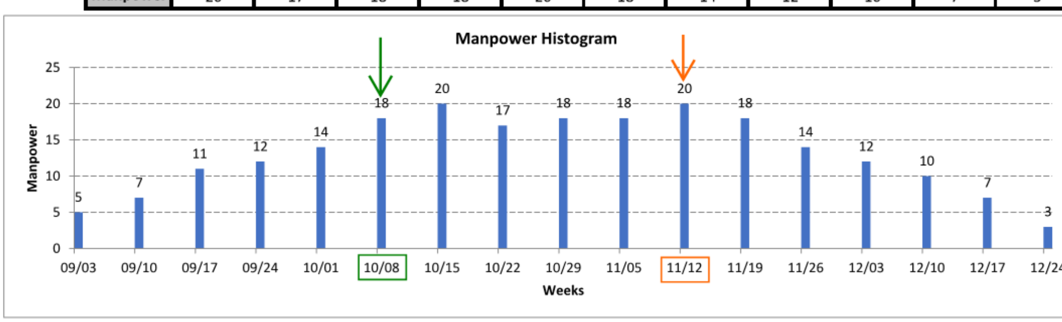

Figure 12: Manpower spreadsheet and manpower histogram

The balanced workfront depicts the optimal amount of work by trade and location-area required per production control period to just meet the as-planned master project schedule completion date without any disruption. Working at the pace of the balanced workfront, the project should not suffer any stoppage due to bottlenecks because all trades will have the same work in process and the same time to handoff their work, one production control period per location-area as shown in the cells of the matrix. Therefore, all trades are working at the flow pace necessary to just deliver the planned client throughput and thus are avoiding bottlenecks. In building construction projects, trade contractors tend to accelerate their schedule so that they can finish their job and move on to other contracts or to accelerate their as-planned payments from later billing periods to earlier ones. However, this often leads to a situation in which areas are not ready for them to start their work, requiring the subject trade to either wait for completion of the preceding trade or to move to some other location within the project to work ahead of another trade. Waiting is a typical example of waste in construction that can be avoided with balanced production management techniques, such as the CFMx. Trades working ahead of the balanced workfront are not adding value but are, instead, creating additional work in process that does not increase throughput nor shorten the schedule.

Handoff Process

In today's building construction marketplace, the installation is often performed by trade contractors rather than by direct-hire employees of the construction manager or general contractor. Trade contractors desire to complete as much work as quickly as possible to not only maximize within-project production but also to employ surplus labor on other backlog work in their portfolio of projects. In building work, it is very important for all trades to realize that their work is tied inexorably to the trades that precede and follow their work in the building, it is the very nature of building construction. Thus, each trade contractor must acknowledge that the project delivery team must work together within a production control plan or framework that delivers a quality product to the client within the time constraints of the construction manager's agreement with the client.

As mentioned before, process flow efficiency is crucial for construction projects, which depends on the handoff process between trades. Each trade supervisor must respect and be accountable to the other trade supervisors to create the teamwork atmosphere imperative to a balanced project. As the team begins to develop, the emphasis on accountability to each other grows and is demonstrated daily, as the preparations for location-area handoffs become the prime topic of coordinating day to day activities. Using the CFMx production control plan, the handoff process transitions or transfers between trades tend to improve over the course of the project. From the beginning to the end of the project, the trades follow the same sequence enhancing the work atmosphere among different trade contractors through demonstrated successful handoffs.

Moreover, the CFMx gives each supervisor transparency of which area their trade must complete in the current period and which area their trade should prepare to undertake for their work during the following period. As the CFMx shows precisely the amount of work (areas) per period during the construction effort, trades have plenty of time to prepare supply chain and other constraints for the pace of the project and establish the ideal crew size. Effective communication among all trades and the construction manager is vital to project success. All project participants must touch base with the schedule status, which must be clear so that everybody can understand. The CFMx provides the information of the project status in one single page.

Assessments of the Clear Flow Matrix

For this paper, two approaches were undertaken to assess the effectiveness and utility of the CFMx: First, work sampling analysis of three different projects where the CFMx has been used and second, questionnaires/interviews with foremen and project managers from subcontractor trades. However, the outcomes of the data collection have the objective of assessing the use of the CFMx in building construction and not giving suggestions for improvements. In the upcoming sections, the outcomes of each one of these techniques will be shown and discussed separately.

Work Sampling Analysis

During the development of this research, work sampling analysis was performed on three different projects where the CFMx has been used, adding almost 12,000 work sampling observations. To bolster the validity of the data, these three projects have different types of construction; Project A is a multifamily apartments project, which has a total building area of 284,788 square feet. The complex will consist of eleven buildings, housing 256 apartments units ranging in size from studios to three-bedroom units. Project B is a school, which consists of more than 72,000 square feet, a two-story classroom building. Project C is healthcare project with 48,000 square feet and two-story building.

<u>Results comparison among three projects</u>

Table 2 and the chart below (Figure 13) compare the work sampling analysis of the three projects (Project A, B and C) using the CFMx. It can be noted that there is a slight difference in direct work among them, indicating that the CFMx has the same outcome for different types of building construction projects.

	Project A-Multifamily Apartments		Project B - School		Project C - Hospital	
	Observations	Results	Observations	Results	Observations	Results
Direct Work	3249	50%	1766	53%	821	50%
Transport	492	7%	255	8%	160	10%
Travel	601	9%	354	11%	198	12%
Instruction	300	5%	155	5%	62	4%
Total Supportive	1393	21%	764	23%	420	26%
Personal	303	5%	112	3%	36	2%
Idle	1556	24%	677	20%	367	22%
Total Idle	1859	29%	789	24%	403	24%
Total	6501	100%	3319	100%	1644	100%

Table 2: Work sampling outcomes of three projects using the CFMx

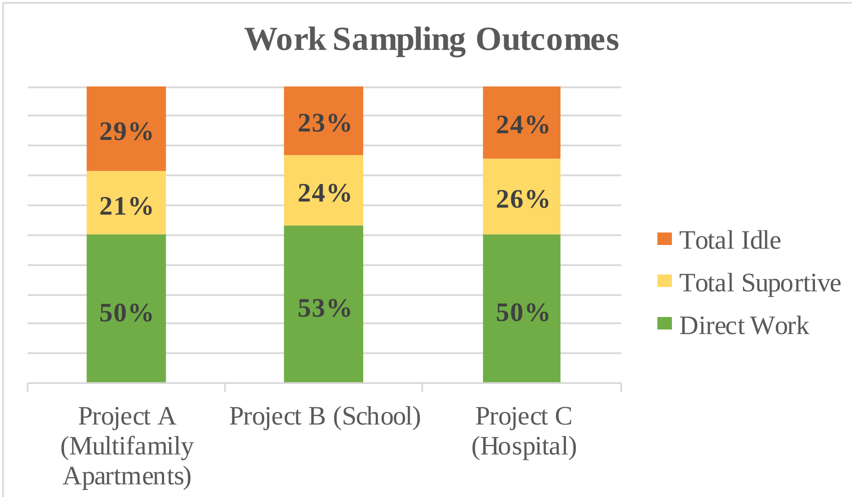

Figure 13: Work sampling outcomes comparison among three CFMx projects

<u>Comparison with the construction industry</u>

Research conducted by Gong et al. (2010) reported work sampling data of 123 construction projects in the Austin, Texas region from 1972 to 2008. This study considered different types of projects such as commercial, highway, hospital, institutional, public and residential. This study was meant to reveal any sign of improvement of direct work ratio over 36 years (1972-2008). The research has detected an overall decrease trend, as shown the chart below (Figure 14).

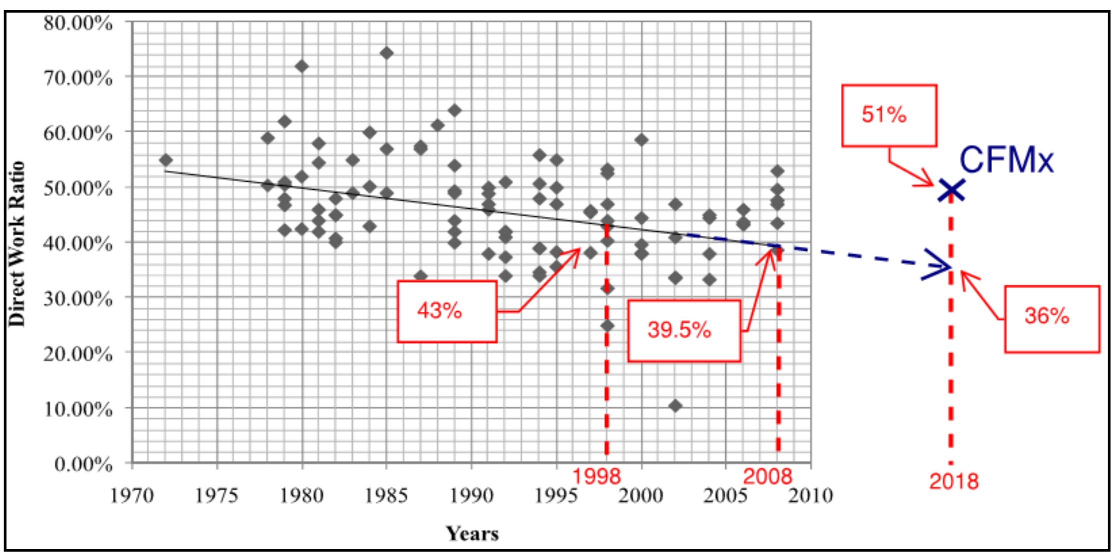

Figure 14: A chronologic view of direct work ratio (adapted from Gong et al.,2010)

The trend line shows that since 1972 the direct work ratio decreases about 3.5% every ten years. For instance, in 1998 the direct work average was 43% and in 2008 (ten years later) this number decreased to 39.5%. If this rate continues for ten more years, the direct work from industry in 2018 is expected to be 36% through the projection of the trend line. Publications with work sampling results found in literature from recent projects could not be used to compare with the CFMx outcomes due to different types of projects (industrial projects) in other areas of the country. Therefore, the trend line developed in the Gong study was used to estimate the 2017-2018 direct work ratio for building construction projects in Texas. As the work sampling data from projects using the CFMx were collected in 2017 and 2018, a comparison between the CFMx and the industry for the same period can be performed. Table 3 below gives an average of direct work from projects using the CFMx, which is 51%, while the trend line gives an average from the industry of 36% for 2018. This means that the direct work ratio is 44% higher for the CFMx projects. The tables below shows the comparison between the CFMx projects and the average of these 123 construction projects from 1972 to 2018.

	Clear Flow Matrix Projects (2017-2018)	Construction Industry Average (1972-2008)
Direct Work	51%	44%
Transport	8%	11%
Travel	10%	14%
Instruction	5%	6%
Total Supportive	22%	31%
Personal	4%	5%
Idle	23%	20%
Total Idle	27%	25%

Table 3: Work sampling results comparison between the CFMx and the construction industry average

Construction Industry Average (1972-2008)	Trend line estimated actual construction industry average in 2018	Clear Flow Matrix Average (2017-2018)
44%	36%	51%

Table 4: Direct work results comparison between the CFMx and the construction industry trend line 2018 estimated actual average

The 128 projects from the study conducted by Gong et al. 2010 encompass seven project types: commercial, public, highway, hospital, industrial, institutional and residential. The chart below compares the direct work rate from this study with the CFMx projects for each type of project separately. This comparison took into consideration only projects that are the same type as the CFMx projects such as residential, public, institutional and hospital.

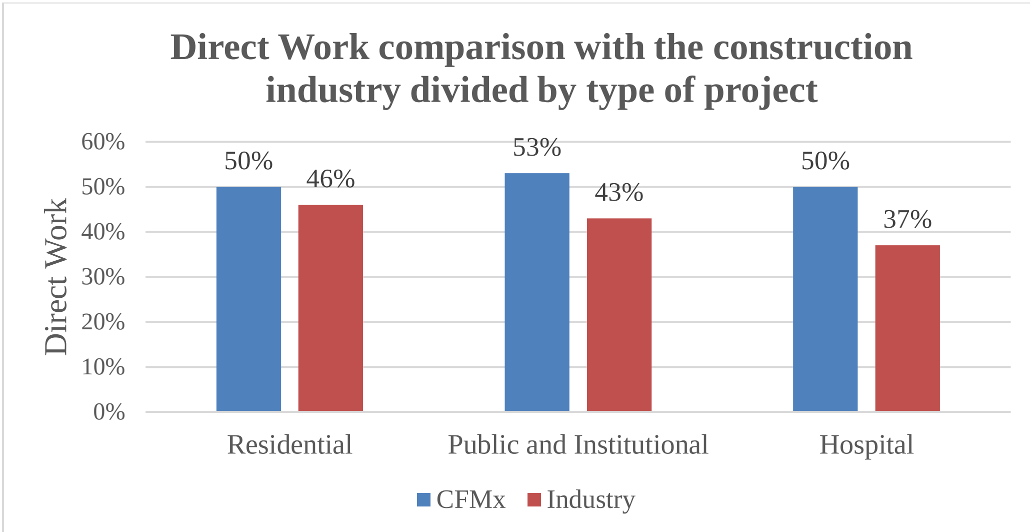

Figure 15: Direct work ratio comparison with the industry on three different types of project (adapted from Gong et al. 2010)

The chart (Figure 15) and Table 4 above indicate that the direct work rate from projects using the CFMx is higher in comparison to the average of the industry. As stated before, work sampling measures the effectiveness of craft time utilization in construction, which is directly influenced by management techniques. Therefore, it is evident that better efficiency was found when CFMx was used in comparison to other techniques used in the industry, of which CPM may have been the most used tool on these projects. It is worth highlighting from Figure 15 the high difference in the direct work ratio of healthcare projects, which is about 35% higher when using the CFMx.

Minimizing waste is one of the strategies to minimize cost in construction projects. Work sampling is a good indicator of waste in construction since it gives the percentage of time spent by workers on the four stages defined by Koskela, where only processing (direct work) is not considered waste in any production system. The CFMx assists project managers to manage their subcontractor trades by providing their exact location every day. Once the sequence of locations is established, subcontractor trades can appraise the amount of work for each area and resources can be better coordinated, and consequently, waste is reduced.

Furthermore, a smooth handoff process between trades is a vital element for achieving high efficiency in construction projects. If areas are not ready for trades to perform their job, the workflow is interrupted, requiring workers from next trades to wait or to move to another spot. Consequently, workers should also transport materials, tools, and equipment to other locations as needed. All these consequences should be evident in the work sampling outcomes. Management strategies play an essential role in handoff processes, which the CFMx controls on a weekly basis. Although the amount of handoffs during the project may increase due to short intervals (one week), this sets a homogeneous handoff duration and increases the plan reliability, since areas to be inspected may be smaller. This ensures that areas will be ready for next trades to begin their work, enhancing the handoff process of the project.

Questionnaire and Interviews

Interviews are considered essential to assess the effectiveness of the clear flow matrix, which is a central topic of this research. Two types of questionnaires for the subcontractor trades were prepared; one for the foremen/superintendents and another for the project managers. The questionnaires for the two groups are not identical, but very similar, differing somewhat in context and perspective. In total, some nineteen foremen/superintendents and seven project managers were interviewed during this research, encompassing as many different trades as practical. The foremen/superintendents were interviewed face-to-face on job sites while the project managers were interviewed either by telephone or in the office. A considerable amount of information was obtained from questionnaire interviews of some 26 individuals affiliated with the trade contractors. The questionnaires used in the interviews of the foremen/superintendents included thirteen questions, and the project manager questionnaire included nine questions. The information obtained from the interviews was grouped according to the following three topics to classify and better assess the answers obtained from the research:

- Benefits and improvements of the clear flow matrix
- Crew size coordination
- Trade-stacking conflicts, rework, overtime, and productivity improvement

Questionnaire Survey´s Outcomes

<u>Benefits using the CFMx</u>

The first topic presented is to demonstrate how the clear flow matrix can improve construction projects. The answers received from project managers and foremen revealed the following key beneficial aspects by using the CFMx:

1. Understandable: The CFMx presents the schedule in a very easy way. Everybody can understand the functioning of the matrix. No engineering knowledge is required to grasp the CFMx.
2. Communication: The CFMx improves the communication among all the project participants. All schedule come together in a single page that can be easily communicated to all levels of project supervision and support.
3. Everybody is involved: This is a consequence of the benefits number 1 and 2. The CFMx is an intuitive technique, and every trade can follow the whole schedule without difficulty. Foremen can track the project without needing assistance from project managers.
4. Easy to manage: There is no need for advanced software to use the CFMx. Only Excel spreadsheets are required. The process of updating the schedule is very fast and easy.
5. Location: The CFMx shows all trade contractors where their crew is supposed to be working every day.
6. Forecast the amount of work: The CFMx presents all the locations and the dates of each activity. Thusly, trades supervisors can estimate ahead of time the amount of work of

each week of the project until the completion date. This helps trades supervisors coordinate their crew size.

7. Schedule on time: Once everybody works at the same pace, it makes the project more organized and keeps the schedule on time.

Coordination of crew size and resources

About 65 % of the respondents said that the CFMx helps the trade subcontractors to coordinate their crew sizes. The CFMx presents the schedule in a simple way in which superintendents may forecast the amount of work accurately for the project by location, allowing them to manage their resources according to the work demand. Each trade on the project receives the CFMx production plan early in the project; the plan indicating the weekly production-by-location, or *the where and when* each respective trade crew would be needed to comply with the construction schedule. For each trade, the amount of workload may vary somewhat from area to area as determined by quantity takeoffs and production information reviewed in relation to the workspace division used in preparation of the CFMx. The CFMx meets the appropriate model of resource requirements elaborated by Birrell (1980), who further states that resources must pass through different locations in the proper trade sequence defined for each project. This sequence of work would typically provide for installation of supporting elements; then MEP utilities; then interior finishes, thus permitting completion of the work. By managing construction projects in a consistent material/work/trade sequence, trade contractors are encouraged to plan their work and procure materials in the correct and repeating order for each location. The successful sequence of handoffs between trades is encouraged through a uniform handoff procedure and consistent communication approach for all project participants. (Birrell, 1980).

Conflict areas, rework and overtime

As it is known that the issues of workspace conflict, rework and overtime adversely affect trade productivity, they were also addressed in the questionnaire to assess the effectiveness of CFMx. Birrell and others suggest that construction management teams may avoid the negative impact of these issues in construction by effective management of production and the sequence of trades. The first topic discussed is workspace conflict, which is very common issue related to schedule acceleration, and arises as trade contractors try to catch up with the as-planned schedule by inserting more workers or assigning multiple and conflicting trades in the same workspace area. However, a study conducted by Thomas et al. (2006) concluded that congested work areas might occur as a result of multiple factors other than just schedule acceleration. The favorable answers from respondents reflects the utility of the scheduling transparency that CFMx provides for project managers of the GCs to avoid such issues. As mentioned earlier, the CFMx shows the location of each trade every week, undoubtedly making the management of subcontractors trades easier than with other scheduling techniques. The concept of production control period is another strong element embedded in the CFMx which enhances the time organization of the project. The production control period and the location breakdown structure encourage all trades to work at the same pace through the locations which results in a more continuous workflow minimizing workspace conflicts of out of sequence installation and instances of congested workspace, or trade stacking.

In regard to rework, the CFMx is a production control technique that promotes the early identification of any design or installation issues before the project reaches an advanced stage. The early identification of such design/installation issues reduces the overall impact of identified issues on schedule and costs through the smaller batch sizes of WIP of the CFMx, enabling the trades to reduce re-entrant work as discovered and appropriate corrective actions are incorporated into future areas as the work progresses. The interviews show this anticipated reduction of rework on projects using the CFMx; about 44% of respondents stated that a reduction of rework was experienced.

Lastly, overtime is a strategy often used to accelerate lagging work to comply with the as-planned schedule. As mentioned earlier, the small batch sizes of the CFMx promoting weekly-production control status updates permits managers and trades to take early corrective actions before longer delays are experienced. The CFMx permits managers and trades to easily identify and visualize on a weekly basis which trades are being impacted by any issue affecting successful weekly handoffs of trade-areas. Such early identification requiring only smaller-scale actions to mitigate issues does not always occur on projects using CPM techniques for production control because of the complex updating required for the many trade-area locations encountered in building work. The interview comments from foremen reveal the efficiency of the CFMx to reduce overtime in construction projects. More than 50% of respondents said that they noticed the reduction of overtime on projects where the CFMx has been used. Figure 16 below shows the outcomes from the interviews.

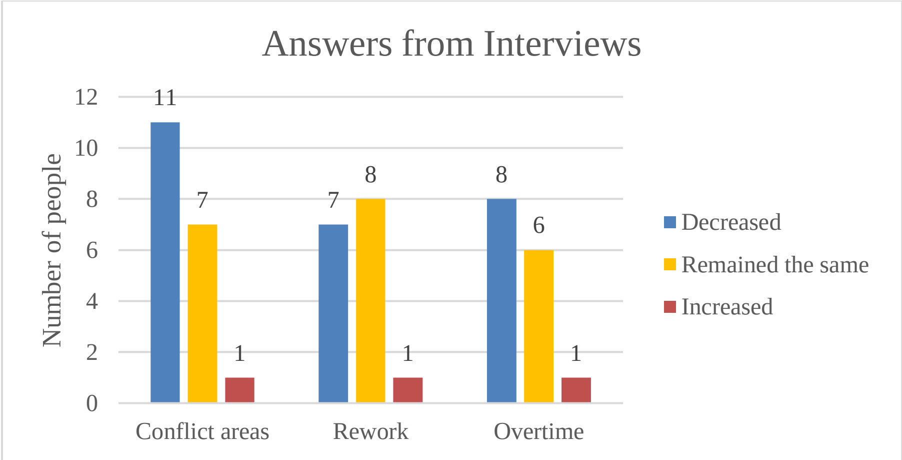

Figure 16: Outcomes about the conflict areas, rework and overtime

The outcomes of three topics shown above bolster the opinion that use of the CFMx would increase productivity on building work. According to the interviews with foremen and project managers about 85% of respondents indicated productivity improvement on CFMx projects when compared with other non-CFMx projects.

Conclusion

A higher direct work ratio of the CFMx indicates a better efficiency in comparison to other techniques used in the industry. A study conducted by Liou & Borcherding (1986) revealed that the direct work from work sampling analysis results can be an estimator for productivity rate. This is one strong evidence that CFMx enhances the productivity on construction projects. The interviews also show positive outcomes of the CFMx. The improvement of productivity is the strongest point uncovered from the answers. Rework, overtime and overcrowded areas are work conditions, which reduce work effectiveness and these topics were discussed during the interviews. The answers from the questionnaires of foremen on job sites indicate a decrease in these three topics, which provided a positive impact on productivity, and consequently reduce cost. It also reveals that management techniques in construction projects influence the productivity of trade contractors. The answers from questionnaire also verify that the majority of companies still use only CPM network analysis and its embedded Gantt chart view as a tool to manage construction projects and required field production. The use of a detailed Gantt chart of suitable detail for production measurement and control typically requires numerous pages of documents in order to schedule the complete project from the start through all trade work and then to completion. This amount of information is difficult for all trade supervisors and field personnel to interpret and update throughout the project. In many applications of the CPM network and Gantt chart technique, the construction manager project personnel communicate the start and completion dates to the trade contractor supervisors and foremen and then the trades are encouraged to work together to complete the project. The CFMx breaks this protocol typical of the building construction industry by providing to all personnel involved in the building project, not only the CPM schedule in a single page but an easy and intuitive production management and control system. The CFMx assists trade supervisors and foremen in the coordination of their crew sizes require to meet the work demand necessary to complete the project according to the master CPM schedule.

In construction projects, project managers of the CM/GC do not have the ability to directly manipulate the operations flow efficiency of trade contractors, which is the responsibility of trades supervisors. However, in their coordination of the handoff process, the CM/GC through their management expertise and responsibility do have total accountability for establishing a successful framework to achieve appropriate process flow as expressed by Shingo in regard to manufacturing. The balanced workfront of the CFMx balances these two types of flow in projects providing the minimum WIP necessary to meet the as-planned master project schedule completion date. in other words, the balanced workfront balances production requirements or quantities of work against the processing capacities of the trade contractors on the project.

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